EROSION AND DEPOSITION IN THE SOUTHERN ARIZONA BOLSON REGION

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Outline of Paper

Structure of the playa muds. (*a*) Chemical deposits. (*b*) Surface markings. (*c*) Animal and plant remains. Erosion of the mud sheet.

CLIMATE AS AFFECTING THE EROSION OF THE BAJADA

Discussion of (1) the remains of an older bajada near Tucson, Arizona, and (2) the incision of the younger bajada by the larger gullies; showing that while climate theoretically might be competent, the facts of the case suggest that other conditions were the immediate cause of this erosion, and finally that climatic changes are better read in the detail of structure and composition of the deposits, rather than in topography.

INTRODUCTION

Before the publication of Barrell's studies on climate and deposition,[1] I wrote:

> It does not seem probable, therefore, that theoretical analysis of the complex relations that obtain between climate and deposition will accomplish what it has in the case of deposition by running water and by glacial action. The problem will be solved by detailed studies in each region. In each case the disturbing factors must be evaluated, and the intensity of each process gauged.[2]

The study of Barrell's article did not seriously affect the above opinion, but it did suggest and encourage the following contribution, on account of the evident value of his analysis in directing attention to the newly developing study of climatic effect on geological processes, in showing its possibilities, and in suggesting some of the criteria available.

In this contribution attention will be confined to a certain definite portion of the arid southwest, which is here called the bolson region. A criticism by Keyes of Hill's definition of the term "bolson"[3] and its use by Tight, Lee, and others gives point to an investigation of the history of the use of the word, and a discussion of its proper meaning.

The data to which this treatment owes its development have been collected during a residence in the arid southwest since 1901. The

[1] Joseph Barrell, "The Relation between Climate and Terrestrial Deposition," *Jour. Geol.*, 1908, pp. 159–90, 255–95, 363–84.

[2] C. F. Tolman, "The Geology of the Vicinity of Tumamoc Hills," *Publication 113*, The Carnegie Institution of Washington (in press).

[3] Hill, *Topographic Atlas of the United States*, U. S. G. S.; Keyes, "Bolson Plains and the Condition of Their Existence," *Am. Geol.*, Vol. XXXIV, pp. 160–64; "Bolson Plains," *Am. Jour. Sci.*, Vol. XV, pp. 207 ff.; "Rock Floor of the Intermont Plains of the Arid Region," *Bull. Geol. Soc. Am.*, Vol. XIX, pp. 63–92; Tight, "Bolson Plains of the Southwest," *Am. Geol.*, Vol. XXXVI, pp. 271–84.

earlier portion of this time was spent in constant traveling over southern Arizona, and northwestern Mexico. In order that the value of the observations and deductions presented may be approximated, it is frankly admitted that until recently attention was not directed to the broader features of desert physiography. The attitude of mind, bent on the study of the details of ore deposition, and therefore investigating minor features so important in that study, was carried over to the examination of the sedimentary deposits, and details of texture and structure, and their possible explanations were readily noticed. It is believed that such a study, undertaken systematically, however, will reveal the intimate relation between climate and deposition.

PHYSIOGRAPHIC DIVISIONS OF ARIZONA

Arizona has been divided into the plateau region, the range region, and the volcanic region by Gilbert, and later by Ransome into the plateau region, the mountain region, and the desert region.[1] A twofold division is preferred for the purposes of this paper, the separating line being the great Mogollon escarpment and its extensions, as shown on Robinson's map of the Colorado Plateaus.[2] The northern portion is designated as "the mesa or plateau region," and the broken area to the south the "bolson" country. The plateau region will not be under consideration, the student being referred to the unsurpassed descriptions of Dutton, and the recent work of Robinson and Lee.[3]

The generalization that this southern region is an intricately broken-down portion of the central plateau is remarkably true considering the broadness of the statement, the regularity of the broken fault-blocks, however, is modified by the complicated post-Carboniferous intrusive masses. Further the form of the secondary hills is

[1] Gilbert, "Report on the Geology of New Mexico and Arizona," *U. S. Geol. and Geog. Survey of the 100th Mer.*, Vol. III; Ransome, "The Geology of the Globe Copper District," *Prof. Paper 12*, U. S. G. S., pp. 14–16, with map.

[2] Robinson, "Tertiary Peneplains of the Plateau District," *Am. Jour. Sci.*, August, 1907, p. 123.

[3] Dutton, "Tertiary History of the Grand Canyon Region," *Mon. II*, U. S. G. S.; Robinson, *op. cit.*, pp. 109–29; Lee, "Geology of the Lower Colorado River," *Bull. Geol. Soc. Am.*, Vol. 17, pp. 275–85.

often controlled by a mosaic of small fault-blocks, showing a remarkably close relation of hills and gullies to blocks and faults. Toward the south and southwest, the fault-blocks develop into parallel strips; ridge after ridge of Paleozoic limestones, and successive sheets of rhyolitic and andesitic lavas rear their heads above the desert-filled wastes. These fault-strips, rather than fault-blocks, are well developed southwest from Casa Grande, the steep scarps facing northeast, and the faults striking northwest, the most important escarpment being that of the Vekol Mountains where several thousand feet of Carboniferous strata are exposed, with an unusual development of upper arenaceous members. The waste between the hills consists of wash deposits, volcanic deposits, playa deposits, and occasional lake deposits, this complicated series dating back through the Quaternary and probably the late Tertiary. Sufficient data have been collected by scattered observations to indicate that in their structure they show the effect of various conditions of climate and topography, and give color to the belief that the history of the Quaternary at least will be discovered by a well-directed reconnaissance of the region.

DISCUSSION OF THE TERM "BOLSON"

With the above description in mind, it is evident that southern Arizona is a region of bolsons, as defined by Hill. He states:

> The bolson plains . . . . are newer and later features consisting of structural valleys between mountains or plateau plains, which have been partially filled with débris derived from the adjacent eminences. [1]

Keyes strenuously objects to the application of the term so defined to the New Mexican examples. He states that the Jornado del Muerto, and Estancia plains are valleys showing erosion bevelment, and are not structural, and that they have but a thin veneer of desert waste.[2] Going farther, he states that New Mexican plains are in general destructional planes, in soft Cretaceous strata with only a thin capping of desert waste, and by assumption these conditions are extended to cover Arizona bolsons. Tight has taken exception to these conclusions as applied to New Mexico, and certainly in the structurally broken country of southern Arizona, the deeply filled,

[1] *Op. cit.*, p. 8. [2] *Op. cit.*, pp. 66, 67.

undrained, or feebly drained areas, corresponding to Hill's definition, exist par excellence. Here there is little danger of confusing soft Cretaceous strata with the later fill.

The following list showing the depths of a few typical wells in the southern bolson region is compiled from a large number of logs furnished me through the courtesy of the Southern Pacific engineers and others. As the wells are sunk only to a good flow of water, the depth of the fill is not known in any case. The Esmond[1] well is especially interesting, as it is situated toward the eastern edge of the semi-bolson of the Tucson District, about five miles from the nearest rock slope, and yet it shows 1,480 feet of typical outwash material. These wells indicate surely more than a "thin veneer" of detrital outwash.

Well	Depth, Feet	Character
Safford S. P. well.........	1,820	Bolson lake beds
Benson S. P. well No. 2...	717	Chiefly bolson lake beds
Benson S. P. well No. 3...	806	Chiefly bolson lake beds
St. David's Artesian well....	530	Chiefly bolson lake beds
Esmond S. P. well	1,480	Tucson semi-bolson deposits
Gila S. P. well............	1,386	Semi-bolson. Lava flow from 1,250 to 1,290
Casa Grande S. P. wells...	615 625	A semi-bolson in Santa Cruz drainage in a region of typical bolsons
Sentinel S. P. well, No. 1..	1,129	Showing 1 lava flow in section
Sentinel S. P. well, No. 2..	962	Showing 2 lava flows in section
Sentinel S. P. well, No. 3..	1,082	Showing 2 lava flows in section and all three are typical wash deposits of a semi-bolson region
Wellton S. P. well.........	1,120	A semi-bolson near Colorado River

The word "bolson" of course is of Spanish origin, and its application by the early Spanish settlers and their descendants shows a keen eye for topographic forms, painfully lacking in the later American invader, who with perfect unconcern will, for instance, designate the surface of a topographic basin as a mesa (a table).

In looking over a collection of old maps of the southwest at the Carnegie Desert Laboratory, I find that "Bolson Mapimi" appears on Thompson's *New General Atlas No. 50*, published in 1814, and since then the word has been in continuous use as a technical geographical term. Hill's definition is faulty in that it imposes a restriction which is only possible of application after the geological structure

[9] *Publication 99*, The Carnegie Institution of Washington, pp. 58, 59.

of the region has been worked out, and not justified, considering the great priority of the Spanish usage.

The geologist is not the only one that has a right to be heard in this matter, for the problems of the desert are being attacked enthusiastically and successfully by the botanist, and it is only by the combined action of the two that the broad problems of desert history and climate will be solved. There is a need for a word by which the individual self-centered drainage systems of the desert can be designated, and we should return to the original and broader meaning of the word bolson. I therefore suggest that the word be used to cover the watershed of a centripetal drainage system, including all the area within the limits of the divides.

The bolson may depart somewhat from a perfect topographical basin, for evaporation on a slope may prevent the development of a through drainage, and foster the centripetal variety. Those bolsons whose surface water *in times of flood* reaches some river thoroughfare, some lower bolson, or the ocean direct, and consequently the playa portion described below is poorly developed or lacking, may be called semi-bolsons. In Arizona, therefore, there is every gradation between bolson, semi-bolson, and ordinary river drainage, the latter becoming more prominent as the Colorado River is approached.

TOPOGRAPHY OF THE BOLSON

The well-developed bolson presents three distinct topographic features. (1) *The Upper Rock Surface.*[1] The slope of this surface is a function of rock structure and composition, and erosive attack. The top surface may be a mesa, developed either on account of protective action of some hard layer, or an older erosional flat, which on the top of the higher mountains is protected on account of the forest growth.[2] The latter are so discontinuous that they have as yet defied any general correlation, and the discovery thereby of a faulted peneplain. (2) *The bajada.* Extending down from the rock surfaces are the flanking detrital slopes,[3] built up by terrestrial

[1] Tolman, *loc. cit.*, gives photographs and diagram illustrating bolson topography.

[2] Example, top of Catalina Mts., north of Tucson, Arizona.

[3] Blake, "The Flanking Detrital Slopes of the Mountains of the Southwest Portion of the United States," *Science*, new series, Vol. XXV, p. 974, states conclusions at variance with those presented here. Probably the best descriptions of all the different features of bolsons are found in Carnegie *Publication 26*, "Explorations in Turkestan."

deposition, the aggradational equivalent of the active erosion above. These slopes are the dominant feature of the arid landscape, each mountain range (or isolated hill under severe climatic conditions) appearing to stand on a symmetrical pedestal. The novelty of these features, and the prominent and distinct place they hold topographically, have led to a repeated request for a formal name. In a former publication already referred to, I recommended the use of the term "slope," describing each particular incline by the name of the mountain which gave it birth: viz., Tumamoc slope, Catalina slope, etc. The difficulty of preventing confusion between the detrital slopes and the rock slopes of the mountains brought out the necessity of a new name for this feature, for which the Spanish word *bajada* has been selected, local usage almost exactly corresponding to the technical meaning suggested. (3) *The playa.* Finally in the well-developed bolsons, there is a central flat, or flats in the irregular and larger bolsons, which is occasionally or even permanently occupied by a water sheet, the life of the temporary lake or pond depending on local climate conditions. In less perfect examples of the semi-bolson this central feature is lacking. In such a bolson, especially where large, the central portion may be a more or less irregular plain, composed of river, outwash, and other deposits, and the general name to be applied is "bolson plains."

ANALYSIS OF GEOLOGICAL PROCESSES IN ARID REGIONS

Torrential precipitation.—Before attention is directed to the aggradational deposits of the bajadas and playas, a preliminary investigation is advisable regarding the action of geological processes under the stimulus of aridity. It is generally assumed that all the precipitation of the desert regions is of torrential character. This is the exaggerated recognition of the fact that there is a marked tendency in that direction, and even where a given shower has no greater density than one in humid region, the run off is more rapid, and torrential concentration accentuated.

Assume a moderately arid region, with a marked tendency toward torrential concentration of precipitation, with both a large daily thermal swing (marked difference between day and night temperatures) and an active wind transportation and deposition. The coarse

material is pried off and made ready for the attack of torrential stream by daily temperature change, and the fine material is brought up by the wind. There is no grading in size between the two, the deficiency of material of intermediate size being marked.

Under the well-known erosion analysis in the case of "a homogeneous island with one depression" let any flood encounter a depression of any kind accelerating its flow, then there *must* be a gullying started which will work up stream. Now the sheet flood described below often flows over irregular ground, and even then its gullying action is almost entirely lacking. The observation of this phenomenon led to an investigation of the manner in which material is transported by flood action. It has not yet been possible to check observation with experimental data, but on account of the bearing on the problems at hand, I present the following inspection of certain phases of this transportation.

Sediments are carried forward by running water in the following three ways: (1) The large material is rolled on the bottom; (2) Finer material is thrown up and down by subcurrents, drifting forward with the current; (3) The superfine is held in suspension by the kinetic action of inter-impact.

1. As is well known the mass of the largest particle that can be rolled on the bottom varies approximately as the sixth power of the velocity of the stream at its bottom. The material rolled comprises the cutting machinery of the stream, and the fact that the size increases so rapidly with quickening velocity, gives to the stream its great power of concentration of energy at declivities and at the down-stream side of hard strata. If a stream is in the rather unusual position of having no coarse material to roll on its bottom, it will not only not be able to cut hard rock, but it will have nothing with which to stir up the finer material in its channel, and therefore its cutting power is reduced.

2. The intermediate and fine material is danced upward by the secondary currents, eddies, etc., of the stream, and during its up-and-down journeys it is carried forward by the current. The formation of these eddies is generally recognized[1] and they are shown in an impressive way in the eddies and whirlpools of the sullen mud-laden floods of the southwest. The whirls are formed by friction both

[1] See Chamberlin and Salisbury, *Geol.*, Vol. I, pp. 111, 112.

along the bed of the stream, and between the layers, as shown in Fig. 1. The bottom whirl can probably be considered of primary importance, because (*a*) at the bottom there is the greatest friction, and therefore, the greatest difference of velocity; (*b*) the bottom whirl has an unbalanced upward velocity: (*c*) the higher whirls have equal upward and downward components, and can affect only the material they have received from the bottom whirls. They will accelerate the upward motion of some particles and retard others to the same extent. Therefore in this preliminary inspection the action of the bottom whirls only is considered. Although the motions will be complex, assume a certain whirl which represents the average upward throw of the stream. Increase the velocity of the stream and the subcurrents will increase presumably approximately directly as the velocity of the stream.

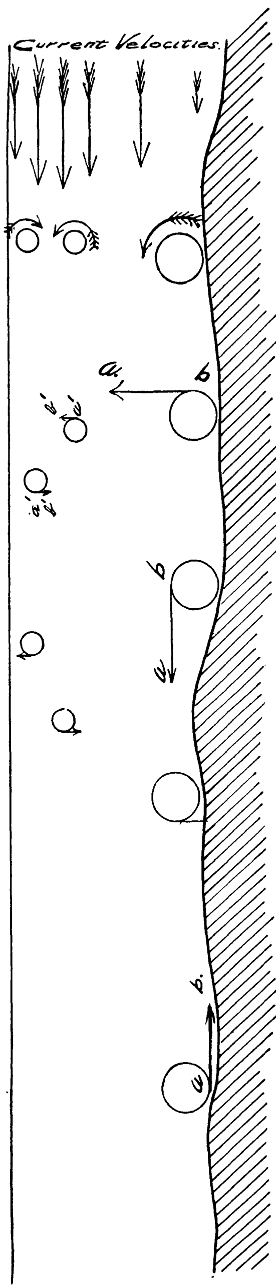

Fig. 1.—The current velocities are indicated at the right. The throw of the bottom whirls is indicated by the arrows *a*, *b*. The small intercurrent whirls have balanced action and receive material from the bottom whirls, and are not important.

Following the course of events as they commonly occur in arid regions, let us assume that the sudden shower or cloudburst picks up a great load of both coarse and fine. Let this shower be on the rock slope of a bolson. There is no dropping of coarse and picking-up of fine material as is postulated for the ordinary stream, because mountain-slope and torrential concentration give a great excess of energy, so

that everything loose on the surface is swept down into the steep canyon. The grade of the canyon decreases below, and deposition commences, boulders first and the rest following in decreasing size according to the v^6 formula for mass to velocity. Here the ordinary backing-up effect is not important. Permanent streams generally develop deposition at a certain point, and this works back, the current damming itself up. The torrent, however, drops its coarse at the top and the rest continuously on its downward path, resembling a single wave rather than a continuous current, so that the effects of deposition are not readily transmitted backward. Wash deposits often show simultaneous dropping of coarse and fine together, as a result of rapid checking of velocity, the formation consisting of a conglomerate of pebbles or boulders set in a matrix of sand or mud, the boulders carried down by the deepest rush of the torrent, and filled in with sand by the subsiding water. Such a deposit indicates clearly the agency of torrential flood. Farther down there may be a spreading-out of the flood as a widening sheet of mud and water. This is the flood sheet, and it may be either the expanded lower portion of the torrent from far above, or the even sheet of run-off from a shower on the lower detrital slope. The coarse material has been dropped, and the fine is now carried wholly in suspension.

The ordinary conception of a loaded stream is one that is picking up material to its full capacity, and also one that has the fine material at hand so that the picking-up and the laying-down are in equilibrium. To increase the capacity of a stream to carry material in suspension therefore, it is necessary to increase either (*a*) the number of bottom subwhirls, or (*b*) the number of particles cast upward in unit time by each subwhirl, or (*c*) the average upward throw of the bottom whirls.

Let these factors be represented respectively by m, n, and d, and L the carrying capacity of a stream for fine material suspended by subcurrents.

$$L \propto mnd. \tag{1}$$

We have assumed certain whirls distributed over the bottom, representing the average upward throw of the stream, and that fine

material of a single size is being transported; therefore m can be considered a constant. Both n, the number of particles thrown upward, and d, the distance of throw, depend upon the velocity of subwhirl, which was assumed above (on account of lack of experimental data) to vary approximately directly as the average current velocity,[1] or

$$L \propto v^2. \tag{2}$$

Assume that in the tumultuous advance of the flood sheet, the average throw of the subwhirls is equal to the depth of the stream (Fig. 2, A), then an increase in the velocity (due to some irregularity in its path) cannot increase d (Fig. 2, B), because the particles cannot

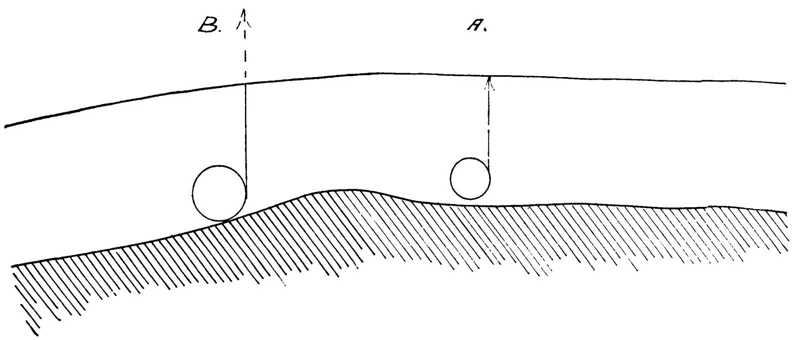

FIG. 2.—A. The average upward throw of the bottom whirl is equal to the depth of the stream. B. The average upward velocity imparted by subwhirl is greater than that necessary to take the particle to the surface.

be thrown above the surface of the water. Therefore under these conditions

$$L \propto v. \tag{3}$$

This shows only a very moderate increase in carrying capacity, not at all comparable with the effect of current velocity on the power to *roll* material forward, which seems generally to have been assumed to govern the eroding power of a loaded stream on receiving an increase in velocity.

In the above analysis, it was assumed that the material shot up by the whirls sinks downward undisturbed by other currents. As a

[1] The Colorado River offers excellent opportunity to study the difference in velocity at various depths in times of flood when silt laden, and in times of clear low water.

matter of fact the whirl must produce upward and return currents. Therefore the effect of increased subwhirl velocity in shooting up a larger number of particles will be in part balanced by a more rapid downward journey of the same particles due to the increased velocity of the complementary return currents. Therefore

(4) $L \propto$ less than directly with v.

Will, however, this moderate increase in power to suspend material be effective under the conditions that obtain in the arid southwest? Is there loose material to pick up? Is equilibrium easily established between the material in the stream and the material on the ground over which it passes? The flood is advancing over a surface that (1) may be a baked mud flow, or (2) is cemented by desert salts, or (3) is protected by pavements described later; therefore it cannot cut, for its tools have been laid down above, and it cannot pick up loose material, for that has been swept away by the wind.

3. It has been suggested to me by Dr. A. E. Douglass, of the University of Arizona, that the finest of the material is not suspended by the subcurrents, but that due to the difference in velocity in the various layers of the water, the numerous superfine particles are in constant collision, and the kinetic bombardment (like that of solutions ascribed to heat) causes a diffusion of particles upward from the region of greatest velocity difference, viz., the bottom. Further, it is to be suspected that the attached air bubbles aid in the suspension of the emulsion, for after boiling a mixture of very fine loess, Dr. Douglass found that the cloud of particles did not rise as readily upon rotating the containing vessel as before. The increasing power to suspend superfine material from the increase in declivity will not cause noticeable erosion, however, on account of a lack of loose fine material of this nature.

We may conclude therefore that a flood sheet is far less responsive to moderate increase of gradient, than an ordinary stream. It is a depositing and not an eroding agency and will not develop into the former even when subject to a moderate increase in current velocity.

As the flood sheet advances its velocity is checked (1) by evaporation, to a minor extent, (2) by absorption in the ground, and (3) mainly by spreading out to a thin sheet, thus greatly increasing surface

friction, the final layer of mud being left at or toward the bottom of the slope.

I have described the ideal case in which the descending water spreads out into the flood sheet. This particular phase, described by McGee, and emphasized by Keyes,[1] while not uncommon, has hardly the importance attached by those observers. It is in every case a depositing and not an eroding sheet, save when confined to a valley where it can do some undercutting, and it is strange that the term "sheet-flood erosion" should have been allowed to go unchallenged so long in geological literature. Final deposition on the margins of the bajada is more often by distributaries, as described by Johnson,[2] although again his statement that the latter is the only method is not in accord with the conclusions reached here.

In any case torrential action develops the three topographic surfaces mentioned above. The occasional storm will accomplish more work, in comparison to the precipitation involved, than more frequent cloudbursts, as the first can carry off the entire supply, leaving the following storms to rework its deposits. Provided that there is no marked change at the foot of the slope, such as earth movements affecting the same, damming-back of the bajada drainage by expanded water sheet, or a quickening of the temporary "through drainage," in the case of the semi-bolson, the initial angle of deposition depends upon a number of minor factors, a few of which are stated below in about the order of their relative value: (1) *Size of abundant fragments*. The relation of upper slope to the coarse material occurring in large amounts, is noticeable everywhere; (2) *Density of precipitation*, and (3) *Supply of detritus*. The largest bajadas should be developed with steepest initial slope where concentrated torrential precipitation is separated by intervals of sufficient time for the development of a large supply of detritus; (4) *Height of mountains above foot of bajada*. Attention will be again turned to the upper margin after climate has been analyzed.

Wind action.—The wind has been given the leading rôle among

[1] McGee, "Sheetflood Erosion," *Bull. Geol. Soc. Am.*, Vol. VII, pp. 87–112; Keyes, *op. cit.*, pp.78–82.

[2] Johnson, "The High Plains and Their Utilization," *Twenty-first Annual Report* U. S. G. S., pp. 612–22.

the physiographic agencies in regions of aridity, by some authorities, while others have given it an intermediate or even a minor importance. The fact is that wind plays a varying rôle from major to minor depending upon the variety of arid climate. This is investigated later and attention is now directed to the method of erosive wind attack and the resistant surfaces developed thereto.

It seems to be commonly believed that wind may attack successfully an unelevated or even a depressed flat surface.[1] It is true that the wind picks up most of the fine material it transports from flat lowlands, but this is largely a repicking of material dropped; of tourist-passenger particles on a stop-over ticket. The source is from certain limited areas that are undergoing erosion on account of special exposure and non-protection.

The larger portion of the surface of the southwestern arid region is fortified against the attack of the wind by desert pavements. Take as an example of extreme development those north of the Chocolate Mountains and west of the Colorado River, protecting an old flood-plain deposit of the latter stream. There the surface is covered with a perfect mosaic of fitted stones, polished and flattened to the last degree of perfection by the wind. The light of the early or late sun is thrown back from uncounted faceted mirrors, in a dancing blaze. Step on this pavement and you are surprised to find the apparently solid rock yielding underfoot. Scratch it with your boot, and you find that there is only a single thickness of pebbles, in size up to an inch in diameter, and at times less than a quarter of an inch thick, covering a deposit of hot, dry dust. A few trips of the wagon in the same tracks, will form deep ruts by the breaking of the pavement. The above description is of the most perfect pavement I have seen, but everywhere, except in the sorted sand of the dune regions, a strong wind develops resisting pavements. The wind attack upon a deposit of dry playa mud, mixed with occasional pebbles (such pebbles are common to all deposits on account of the vicissitudes of arid deposition) must proceed as follows: First (provided no crust deposits interfere), the wind can blow just as much dust as contains on the average a single layer of pebbles; second, this layer of pebbles

[1] Davis, "The Geographical Cycle in an Arid Climate," *Jour. Geol.*, 1905, pp. 385, 388, 391.

must be laboriously sandpapered to nothingness, before the second layer can be touched. MacDougal[1] reports that wheel tracks were seen on his trip into Lower California, that had been made sixteen years ago, and that the gun ruts of the Walker Filibustering Expedition are reported to be still visible in places after fifty years. In fact, a wheel track on such a pavement as is described above would last indefinitely according to ordinary popular measurements. The polishing of a horizontal surface is striking, but the erosion accomplished by this action can easily be exaggerated. The wind motion is nearly tangent to the ground, and the sand is danced lightly off a flat surface. Let a projecting face withstand the wind, however, and it immediately concentrates its energy to the work as vigorously as a youthful river to an opposing hard stratum. The maximum work is done where a crumbly horizontal sandstone attempts to withstand the wind. Here no talus protects the face of the cliff, and the opposing strata are completely chiseled off before the blast.[2]

The wind will undercut by working in the least resistant layer, the amount of this carving being limited by the talus from the harder layer above. Even the talus, however, is exposed to the windblast, and its removal may be assisted by torrential water, and yielding rapidly or slowly allows fresh attack on the cliffs.

A study of almost any erosion forms in an arid country shows undercut wind action, and further description is unnecessary. The action being most effective against vertical faces of horizontal strata, the wind terraces are driven back along the weak layers. There can be no question but that much of the amphitheater work of the Grand Canyon of the Colorado, and the level steps of the high plateaus of Arizona and Utah are developed by wind erosion.[3]

Underground water.—The depth at which underground water is encountered in bolsons is very variable. Considered in relation to surface geology, however, interest is not so much attached to the underground water table as to the surface moisture table. Recent

[1] MacDougal, "Botanical Features of North American Deserts," *Publication 99*, Carnegie Institution of Washington, p. 96.

[2] Whitman Cross, "Wind Erosion in the Plateau Country," *Bull. of the Geol. Soc.*, Vol. XIX, pp. 53–62, a striking example of the above.

[3] Keyes, *op. cit.*, pp. 81–83, 85–91, an extreme estimate of the importance of wind erosion.

experiments in dry farming show how a moisture table, elevated far above the water level, can be developed and protected by cultivation.[1] The crust deposits of the semiarid regions are believed to be developed by a similar moisture table. The rainwater penetrates with difficulty the dry soil, and while a portion may gain the larger openings and sink to the underground water level, a larger portion is caught in the capillary pores and drawn upward by the drying-out above, and laden with mineral salts deposits its load as the "caliche" crusts,[2] through evaporation at or near the surface. These crusts are built into the deposits, and are slowly recrystallized, forming the calcareous, gypsiferous, and even siliceous cement of the cement-gravels. The well sections examined in the vicinity of Tucson show that the amount of the cemented gravels may rise to 80 per cent. of the whole. Possibly the "mortar beds" of the high plains of Kansas, for which Johnson could find no adequate explanation[3] were surface crusts formed under local conditions of aridity, by means of an actively evaporating moisture table, and covered by subsequent deposits.

CLIMATE

I believe that in the future, when the recognition of climatic effects in sedimentation becomes general, the value of the recent articles by Barrell and Huntington[4] will be highly rated. Climate itself, however, needs still further analysis before its effects can be read satisfactorily in the strata. The critical factors from the erosional and depositional standpoint have not yet been determined, especially those that are in a measure the independent variables, nor has the

[1] See *Bulletins 103* and *130*, Bureau of Plant Industry; also Livingston, "The Soils of the Desert Laboratory Domain," *Publication 113*, Carnegie Institution of Washington; *Bulletin Agricultural College of Utah, No. 91;* Alway, "Studies of Soil Moisture in the Great Plains Regions," *Jour. Agricultural Science*, Vol. II, pp. 333–42.

[2] For description and discussion of the caliche see Blake, *Trans. Am. Inst. of Mining Engs.*, Vol. XXXI, pp. 220–26; Tolman, *loc. cit.;* Lee, *Water Supply Papers, No. 136*, U. S. G. S., p. 111.

[3] *Op. cit.*, pp. 643–57.

[4] Barrell, "The Relation between Climate and Deposition," cited above; "Relative Importance of Continental and Marine Sedimentation," *Jour. of Geol.*, Vol. XIV, 1906, pp. 316–56, 430–59, 524–68; Huntington, "Some Characteristics of the Glacial Period in Non-Glacial Regions," *Bull. Geol. Soc. Am.*, Vol. XVIII, pp. 351–85.

effect of the swing from one kind of climate to another received more than introductory treatment at the hands of Barrell.

Climate is the product of complex causes, a few of which may be considered the critical factors, and the rest quite subordinate. Barrell's classification of climate into warm and cold humid, and warm and cold arid, or again into constantly rainy, intermittently rainy, subarid, and arid, group together certain more or less decided expressions of climate, the fundamental factors of which may vary considerably, and, moreover, under the present practice of compiling weather data, these differences, some of major importance, could not be detected. The present unsatisfactory state of climatic analysis may be realized by comparing the conclusions of Barrell and Huntington in regard to the climate oscillations in regions outside the ice-sheets during the glacial epochs. Barrell suggests that in certain regions increasing cold may increase rock disintegration, without a corresponding increase in the transporting power of the streams, and therefore the outwash deposits may have been built up steeper as a response to the increasing cold of the glacial period, and on swing to a warmer climate there was erosion.[1]

Huntington explains that in the arid regions of Asia the moist (glacial) epoch accelerated the weathering of rock and growth of vegetation. Therefore waste was stored in the upper valleys of the mountains. Aridity followed with torrential precipitation and the destruction of vegetation, therefore the stored material was washed down on to the bajadas, and later, the supply from above giving out, these outwash deposits were dissected. Therefore each swing from glacial to interglacial is represented by a terrace.[2]

In reaching these different results in regard to the glacial-interglacial swing in elevated subarid regions, different sets of critical factors are assumed. It is not unlikely that both assumptions are correct and that the variations in different factors occurred at different times. It surely therefore is profitable to find out if possible what factors are of quantitative importance, and what range of play is possible between them.

[1] *Op. cit.*, pp. 172, 173. Barrell applies this to the dissection of the Gila Conglomerate. The author has reached a different conclusion which he hopes to present in a later contribution.

[2] *Op. cit.*, pp. 357, 358.

We must assume that there are certain areas of the globe which have had a dominantly arid climate as long as the atmospheric and oceanic circulation and the shape and relief of the continents resemble that of today. Doubtless those tracts whose arid condition is due chiefly to the trade winds have had a more continuous and a more steady arid history, than the deserts of the northern regions due mainly to topography. We have had the curious anomaly in the development of a geological philosophy during the last twenty years permitting, on the one hand, the upthrust of a continent thousands of feet, on the evidence of a slightly river-scarred plain, and, on the other hand, an almost universal assumption of climatic constancy, that could not possibly exist in view of the movements involved. Fully as curious are the physics involved in the earth movements necessary to make the lakes hold water, and then discharge the same again, in which the shifting piedmont and outwash deposits (erroneously interpreted as lacustrine) have been assumed to be laid down.

In the bolson region it is believed that if only there is a general dominance of arid conditions, a very considerable swing from arid to humid and back again is permitted. The through drainage of the moister climates has had great difficulty in cutting through the great talus and rock slopes which aridity has carved and built up into undrained basins.

While aridity depends primarily on deficiency of precipitation, variations in the same may take place along the following lines:

TYPES DEPENDING UPON THE DISTRIBUTION OF PRECIPITATION

Type 1. Torrential concentration of rainfall: (*a*) with moderate rainfall; (*b*) with deficient rainfall.

Type 2. A distributed and gentle rainfall, moderate in amount.

Type 3. A distributed and gentle rainfall very deficient in amount.

Torrential concentration.—The importance of torrential precipitation need not be investigated here. All writers are unanimous in giving it an important rôle. The general assumption seems to be that torrential concentration increases with aridity. It should be emphasized, however, that we have not the observational data to properly gauge this factor. The weather bureau arranges its data along *average* lines. Average daily, weekly, monthly, yearly tables

are given and doubtless later we will be told the average of the century. A knowledge of the average precipitation tells us little. The observations should also be arranged to determine the density of the precipitation, the unit taken being a rate of fall measured in centimeters per hour, then the figures for the rate of fall of each shower, or the most violent portion of the same would furnish some numerical foundation for further deduction. The assumption that increasing aridity always involves increasing torrentiality is not wholly justified, for conditions can be set up deductively which will cause an increasing precipitation of increasing torrential character.

In this preliminary analysis, therefore, torrential concentration is chosen as the first of the important factors governing desert climates. Livingston reports[1] that summer rains in Tucson often reach the amount represented by 1 cm in ten to fifteen minutes, and I estimate that, under the conditions that there obtain, a density of 3 cm per hour can probably be considered the lower limit of torrential precipitation.

The climate of the Salton Sink and San Felipe desert in Lower California is a good example of Type 3. MacDougal states[2] that the rainfall is distributed through the year so that only a small precipitation is received within any one month, and that at the Raza Islands no precipitation occurred for more than an entire year. At Fort Yuma the average for twenty-six years is 2.84 inches per year, with a fairly even monthly distribution, excepting a notable decrease for April, May, and June. This region shows to a marked degree the increased importance of wind action, and the extensive slopes are of gentler gradient than those developed under more torrential conditions. Without carrying analysis farther it is safe to conclude that under a non-torrential and distributed precipitation, the main quantitative factor is the increase in the relative importance of the wind action.[3]

If now rainfall increases moderately without decided torrential concentration, it is probable that vegetation, especially the grasses and the forests, will increase in importance, and the material of rock disintegration is held back, chemical weathering starts, talus slopes

[1] *Loc. cit.* [2] *Op. cit.*, p. 43.

[3] See Douglass, *The Crescent Dunes of Southern Peru* (in press); (Tolman, "The Crescentic Dunes of the Saltan Sea," *Jour. of Geography* (in press).

decrease in inclination, and also are protected against removal by grasses.[1] Here then the factor of increasing importance is the protective sheet of vegetation.

Effect of temperature.—Here again the extreme *daily* difference in temperature at the naked rock surface is desired, and the abundant data compiled from observations taken under shelters, etc., are of little value. Further, in the attempt to discover those factors of primary importance, all changes of longer period may be overlooked. Where the freezing-point is crossed daily, we probably have one of the maximum points in temperature change action, and where the rock surface remains above or below freezing for more than a day, the effect is diminished.[2] Here again there is a chance to gather further information, at moderate outlay of trouble, by placing self-recording thermometers on exposed rock surfaces, at different altitudes and times of the year in desert regions. It is evident that daily temperature is a variable, at least partially independent of the distribution of the rainfall, and after data have been collected its separate analysis as a climate factor should be attempted. Summing up we find that the following varieties of desert climate are important:

Type 1. Torrential Precipitation Dominant

Torrential distribution...	A—extreme or B—moderate	in either case with daily temp. diff.	*a*) extreme or *b*) large

Type 2. Protective Plant Covering Controls

A moderate and distributed rainfall with no great extremes of daily thermal change.

Type 3. Wind Action Important

A thin distributed rainfall grading to no rainfall.	and daily temp. difference	*a*) extreme or *b*) large

DEPOSITS OF THE BOLSON

The Bajada Outwash. Inclination.—In the moderate torrential conditions of southern Arizona, the middle portion of the slopes varies from 50 to 300 feet per mile. The grade of this middle portion appears remark-

[1] Johnson, *op. cit.*, p. 625.

[2] See Barrell, *op. cit.*, p. 172, for a summary not entirely in accord with the above and for a list of authorities; also C. and C., *Geology*, Vol. I, pp. 44–48, and MacDougal, *op. cit.*, pp. 77–79.

able even to the eye, and shows on the topographical maps by the even spacing of the contours. The grade increases on approaching the rock surface, and in extreme cases, especially where the slopes lead up to volcanic hills where undersapping by wind is prominent, it approaches the angle of repose for the material of which it is composed. It is distinguished from the upper margin of lake and ocean deposits by the absence of wave-built and wave-cut terraces, and the flat upper surface of the top set of the delta, etc.

Upper limit.—The line traced by the contact of the detrital material with the rock surface invariably extends up every gully and down around every ridge. With lake or ocean deposits a level upper line is scarred into the landscape by beach and cliff action.

Size of material.—The astonishing size of the boulders found in the outwash, with other phenomena described later, has led to a local popular appeal to glacial action. Boulders up to six feet in diameter are found in the Catalina and Santa Rita outwashes near Tucson, for a distance of half a mile from the present rock surface, and boulders at least two feet in diameter six miles and more from the present ranges. In ocean deposits occasional distribution of material of this size below cliffs only is noted.

Shape of boulders.—They are generally subangular, although some are partly rounded by their tumultuous journey.

Decomposition of the material.—Almost no decomposition of either boulders or smaller material was noted in the various bajada deposits examined; so much so that grave difficulty is encountered when attempting to account for the large amount of calcareous cementing material often present.

Sorting.—Layers of sized and clean sorted boulders, gravel, and sand are discovered but more often sorting is completely lacking, although stratification is always excellently developed. Pebbles are found in a matrix of sand, and boulders in a matrix of clay. In extreme cases the latter may not be due to water action. For instance, about two miles northwest of Travertine Point, Salton Basin, California, talus deposits, remnants of old slopes, were filled in with wind dust, and proved treacherous to climb. This is a deposit formed under extreme conditions of great daily temperature change and small non-torrential precipitation.

Arroyo trains.—The larger streams often run, for a portion of their course, at least, below the surface of the bajada, and nevertheless their work may be on the whole aggradational. Down such channels the streams bring large boulders, forming extensive radial deposits of rock trains.[1]

Sand pockets.—In the larger stream bottoms, especially in the cross drainage when developed at the foot of the bajada, deposits of perfectly sorted sand occur in "whirl pockets" sometimes composed of clean mica, forming then bad quicksand deposits.

Changes in layers.—The shifting character of the aggrading streams records itself in the rapid wedging-out of the layers. This is especially well shown in Tucson well sections where the boulder layers in adjacent wells do not occur in the same place in the column.

[1] Tolman, "Notes on Desert Processes and Desert Deposits," *Journal of the Proceedings of the Annual Convention of the Arizona Miners Association*, 1905–6, p. 15: "The distribution of coarse material in the outwash desert deposits is in some ways remarkable. The larger stuff is, of course, somewhere in the vicinity of the mountains. It is also distributed to great distances down the temporary torrent channels. To appreciate what is accomplished in these waterways at a distance from the mountains, it is necessary for one to have seen some such a display as I once witnessed on the desert plain between Altar and Puertocito on the road to Santa Ana, Sonora, Mexico. I was driving with no thought of rain, when suddenly I came to one of the numerous washes that cross the road, and found it filled to the brim with a foaming roaring flood, which was as impassable as the Niagara. Looking towards the mountains perhaps ten or fifteen miles distant, I noticed for the first time the black speck of the cloudburst, which happened to be at the headwaters of this arroyo and no other. In a few hours I was able to cross, and on my return found some boulders to approach three feet in diameter. And this was ten to fifteen miles distant from the mountains! On the west slope of the Santa Rita mountains (east of Tucson) there is a ridge of rocks that was piled there by a torrent which later took a different course. These large boulders have remained invincible against the subsequent attacks of the water. This deposit has been mistaken for the moraine of an old glacier. . . . . The rate at which the mountains are torn down and the outwash deposits are built up, is rapid indeed when compared with the slower processes of ordinary erosion. As an example of this rate I shall mention the fact that the bottom layer of the Tucson outwash deposit, south of the Santa Catalina mountains, contains fragments of porphyries and lavas which do not appear in place on the south side of the range. The conclusion is evident that this layer represents a portion of the mountains entirely washed away. . . . . Sometimes great boulders are found at some distance from the mountains. I recall one case where, between a great boulder and the parent mass from which it had been detached, there was a short ridge or knoll fifty feet high. I was asked how the boulder could have traveled up over the hill to its present position without the aid of ice. I answered 'the surrounding country has been washed away and the hill left as a remnant, since the boulder rolled down from above.'"

Stratification.—The stratification in outwash deposits is especially developed. The alternate floods, of varying volume, now carry mud and now boulders, both depositing. Also the wind action described sorts out a protective layer of larger pebbles. The crusts develop a more or less stratified form, especially where the surface is level. This is, however, modified by a dome structure, due to the drying-out of the slightly elevated portion, causing a capillary flow in that direction, and accentuated by a slight erosion of the hollows.

Playa deposits.—The deposits of the playas vary considerably especially as they are formed (1) under a water sheet of moderate depth; (2) in a thin sheet as an evaporating mud surface; (3) as a flood-sheet deposit from a strong flow from above; and (4) these are all modified by wind erosion during periods of aridity. The strata deposited under lacustrine conditions need not be considered here, as the details of such deposition have been under geological observation for many years. An excellent summary of the details is found in Barrell's articles, cited above. Summarizing some of the points of especial import, the following are noted: (1) The strands and terraces of inland water sheets comprise some of the first of the climatic criteria discovered by geology; (2) coarse material is distributed in belts, parallel to the strands, and found only in their vicinity; (3) the deeper muds are largely wind-borne, and therefore of even fineness; (4) lack of subaerial markings of all kinds, within the body of the deposit, as well as of oxidation, are the chief features separating lacustrine from playa and subaerial delta deposits; (5) thick beds of pure sorted mica, floated out into deep water (observed in the Painted Canyon series, Mecca, California), indicate deep-water deposition under arid conditions.

On account of the lack of dissection of the playas visited, less data have been gathered on this subject than on the others.[1] Some of the characteristics have been inferred from observations on playas in the making.

Chemical deposits of the playas.—The chemical deposits of the playas are the more soluble salts, while that of the lower portion of the surrounding bajada is largely carbonate of lime.

Playa mud. Subaerial characteristics.—The well-known markings

[1] For characteristics discovered by Huntington in Turkestan, see *op. cit.*, p. 286.

due to the drying of a mud sheet show extreme development here. Wind, sand, and salt often comprise the filling of the mud cracks. *Mud crack tubes.* At the margin of the Salton Sea the drying-out of irregular mudcracks develops a surface crust of salt, arching over the crack. When well developed these become perfect tubes, and simulate the salt crusts deposited around small roots, or even fossil tubes of worm burrows. *Shallow channels caused by wind erosion* were excellently developed on the Salton beaches, and might find preservation in fossil playa deposits. Where the playa develops alternate extended and lacustrine conditions, restricted with well-developed beaches, dune formations, and blown-sand deposits, with plunging and truncated structure, invade and cover the playa muds. Special development of dune and standing-water action was noted in the area of the Crescentic Dunes, Carrizo Sands, Salton Basin, which explains some irregular structures showing fragments and lenses of wind sand in shale, noted especially in the Painted Canyon series, Mecca, and deserves, perhaps, at least a passing notice. Between the individual dunes, the ground is strewn with rock fragments, composed largely of pieces of strongly cemented dune sand, and protruding above the surface is a most irregular wind-sand formation, also cemented. Its irregular truncations and bevelments showed plainly that it was built up of truncated bottom layers of dunes that had passed over, leaving behind their bottom layers, captured by the salt seepage water, and later cemented by limonite, the whole formation showing the extreme conditions under which it was formed.[1]

Animal remains in playas.—Judging from the large number of bogged cattle that perish in the Arizona "cienegas" (fresh-water mud flats) during periods of drought, the same ought to be expected in older playas. Salt water would not attract the animals. The wind-rows of decaying fish that occur after flood intervals, in the Laguna Maquata, described and explained in the following quotation, are suggestive in connection with the development of petroleum, in strata deposited in arid regions suffering from periodic invasion by a strong river or the sea.

> This low ridge of dead fish was seen to extend for about 15 miles and may have been double that length. A similar observation was made by Orcutt in

[1] Tolman, *loc. cit.*

1890, who found that the remains at that time were of mullet. From other sources it seems fairly probable that nearly every flood brings with it shoals of fish which find their way into the laguna. The shallow sheet coming in over the plain to the southward must furnish abundant food: but as the water rises in temperature and increases in concentration, it seems quite probable that a point is reached at which the water becomes poisonous to all of the finny inhabitants. Furthermore, this condition ensues at once and with sweeping effect, for the dead fish go ashore during so brief a period that no marked change of level has taken place; and as evaporation may be as great as half an inch a day, and scarcely ever is less than a quarter, the disaster must take place within a week or two.[1]

Plant remains.—There is a decided dearth of fossil remains on both bajada and playa deposits. In regard to the former this is to be expected, due to complete oxidation and lack of exploration. The playa deposits, especially the fresh-water playas, and the cienegas of the semi-bolsons would be expected to contain more in spite of subaerial exposure, for wood decay is extremely slow in arid regions, and the dense clay ought to help preserve the more resistant portions of the plants, such as the sahuaro ribs and such hard woods as mesquite. The prompt decay of the mesquite wood which was immersed under the expanded Salton Sea, and now exposed, suggests that even a small amount of salt dissolved hastens decay, for the Salton water contained (June, 1907, about 2½ years after the first break of the river into the basin only) about four times as much salt as the Colorado River at low water, and even now it is possible to drink the water under stress of necessity.[2] An interesting problem demands solution as to whether or not the Tertiary deserts were more deficient in plant covering than those of today.

Erosion of the dried playa.—This is entirely by wind action. The smaller the playa the more likelihood of desert pavements, on account of the larger proportion of pebbles contributed by the floods from above. Such fossil wind-erosion surfaces have been noted in deposits examined.

Relative importance of lake and outwash deposits.—A brief reconnaissance in the Salton Basin gave a good chance to compare the relative importance of the lake deposits, and those laid down in the bajadas. This basin has suffered many invasions by the river water,

[1] MacDougal, "The Desert Basins of the Colorado River," cited above, pp. 16, 17.

[2] For analyses, see MacDougal, *op. cit.*, p. 3.

each time forming a "sea." Many of these seas were sufficiently long-lived to develop excellent strand phenomena, and yet the basin, over which these advances and stays of the water took place, shows a most insignificant proportion of lake deposits compared with the detrital outwash from the mountains. It is little wonder that the early explorers, attributing all the depositional work to stan ing water, formed a very erroneous idea of the relative importance of lake deposition, and extended the sphere of its action far beyond that warranted by facts.

EFFECT OF CLIMATE ON THE EROSION OF THE BAJADAS

Turning again from facts to theory, let us investigate the effect of climatic variation on the erosion of the upper margin of the bajada. Space forbids a discussion of all the possible variations of climate on desert erosion, and moreover the profit resulting from such a theoretical discussion is very problematical. Even the limited investigation presented is more for the purpose of showing how complicated are the relations obtaining, and to emphasize the quotation which appears at the beginning of this article, rather than to develop working criteria.

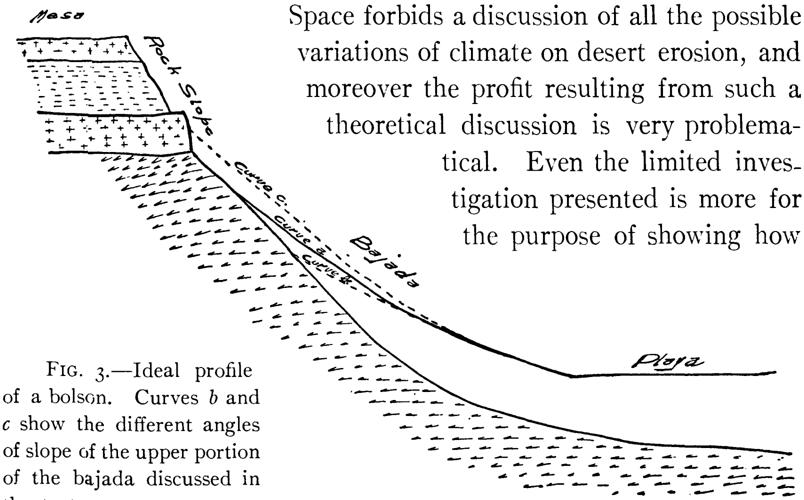

FIG. 3.—Ideal profile of a bolson. Curves *b* and *c* show the different angles of slope of the upper portion of the bajada discussed in the text.

Assuming that a playa is unaffected by earth movements that might displace it relatively to the surrounding bajadas, or by erosional attack of through drainage discharging to a lower level, a gullying from top to bottom would hardly be expected, and a minor incision especially of the upper portion would be more common. The initial slope is profiled by curve *a*, Fig. 3. Curve *b* shows the equilibrium

line with a lower angle of slope, a state of affairs that will result in the gullying of the bajada, while curve *c* indicates a condition that would result in rapid deposition. That such an erosion of the upper edge takes place irrespective of the conditions at the foot of the slope, is indicated by the fact that there are gullies which develop in the upper slope, but fade out before the bottom of the outwash is reached. Furthermore, an important criterion is discovered at this point. Should the bajada be gullied sharply from top to bottom, the cause may well lie in some change affecting the level of the playa, or the outwash drainage of the semi-bolson. North of Tuscon, in the Santa Catalina Mountains, there are remnants of an older and much higher bajada, than the well-developed lower and gullied slope. Preliminary studies suggested that this erosion might be connected with climatic change, but later it became evident that this was directly connected with the drainage developing at the foot of the slope.

Theoretical analysis, then, teaches us to look for variations of climate written in the upper slopes of the bajadas. The following is a list of those that ought to be most easily recognized:

Change in daily temperature difference variable, other factors remaining constant.

Change in torrential concentration variable, other factors remaining constant.

Change in plant covering variable, other factors remaining constant.

More effective still would be the immediate result of a decided swing, say from an effective daily temperature difference, to a marked torrential concentration, or the destruction of a heavy plant covering by aridity and a torrential concentration. Such possible factors were considered in attempting to explain the formation of the decided gullies that issue from the larger canyons of the Santa Catalina Mountains, and have incised the recent bajada,[1] but on close consideration it seemed more probable that these could best be explained by the fact that they drain a large area back in the mountains. The higher watershed receives more of the non-torrential winter rains, while the lower lands receive a larger proportion of their precipitation in the summer months and of a markedly torrential variety. The winter streams maintain a constant flow for several months, and are

[1] See the Topographic Map, Tucson Quadrangle, Ariz., V. S. G. S.

underloaded, and therefore slowly cutting. This erosion would be increased merely by increasing the proportion of winter precipitation to the whole.

Some idea of the delicate balance between climate and geological processes is gathered, when one considers that a slight shifting of the precipitation from the summer to the winter seasons produces a marked effect in erosion. Furthermore, differences in rock structure are more reliable as records of past climate than erosional features, so full of double meaning. Further investigation into possible criteria of climate change will not be undertaken here, although all the criteria suggested by studies so far have not been exhausted. If I have suggested some of the possibilities of the final results of this study, some of the working methods to be applied, some of the points that call most urgently for investigation, and some of the results that may finally be expected, the purpose of this contribution will have been fully accomplished.